Calculating Pressures of Formation Using Chemical Analyses of Glasses from Transform Faults along the East Pacific Rise

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By

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Abstract

Magma crystallization properties and processes are under-studied and are not well understood in transform faults at mid-ocean ridges. Some crystallization pressures that have been calculated along the East Pacific Rise are very high when compared to eruptions on normal ridge segments, but the magmas do follow normal crystallization trends. Overall we do not know the exact conditions of crystallization for magmas along transform faults. This research focuses on the Blanco, Clipperton, and Siqueros transform faults. By analyzing data that were collected for eruptions along these three transform faults in the East Pacific Rise, we calculated crystallization pressures and compared them to known data and to each other to understand the processes occurring at depth. Results showed that these magmas have pressures within the expected range for intra-crustal crystallization, and they also show evidence for magma evolution associated with normal crystallization processes. Some samples had extremely high partial crystallization pressures, but they also had inconsistent and unusual chemical characteristics, so they cannot be assumed to have recorded the actual pressure of crystallization.

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Introduction

Our entire planet relies on geologic processes occurring continually over vast amounts of time. Tectonics effect our ocean cycles that in turn effect entire ecosystems and even the atmosphere as a whole. The current state of the Earth has been shaped over billions of years, and one of the major driving forces for all geologic change can be attributed to plate tectonics. As much as we study this phenomenon and other processes, there is only so much that we can observe, and must infer a lot about past conditions that lead to what we can currently see and study. We can map complex formations, use fossils to correlate different areas on this planet to each other, and identify lithologies thousands of meters below us with the use of seismic data and well log technology. All of these processes are challenging in their own way, but one of the least known is how and why mid ocean ridges behave the way they do.

Although much work has been done with mid ocean ridges, they are challenging to study because they are located below kilometers of water. We have developed techniques to study these ridges over time such as sonar to map the topography of the sea floor, observing the alternating magnetic field of the earth that is preserved in the sea floor, and even collecting physical samples from the seafloor to study the composition and variations within. Despite the amount of research done so far, there is a wealth of information that has not been discovered. Mid-ocean ridge basalts provide valuable windows into the Earth's mantle. These oceanic basalts are not prone to the degree of contamination often observed in continental lavas that results from their passage through thick continental lithosphere and crust. Mid-ocean ridge basalts (MORBs) form by partial melting as the ascending mantle beneath spreading ridges reaches its solidus temperature, and MORBs are generally accepted to represent a broad sampling of the convecting upper mantle. My research focuses on transform faults at mid ocean ridges in the East Pacific

Rise (EPR) and analyzing the geochemical composition of their magmas which then can be used to calculate the pressure that the magmas formed at. By collecting data sets at three of these transform faults, the Blanco, the Clipperton, and the Siqueros, we calculated the pressures of partial crystallization of magmas which erupted along these particular areas. In doing so, we develop an understanding of the formation of oceanic crust and delve into the processes that occur at transform faults.

Background

Mid ocean ridges (MORs) are arguably the most important geologic feature of our Earth because they drive tectonics and shape the whole world. They are divergent margins on the ocean floor between crustal plates where magma from the asthenosphere rises to the surface, forces apart the tectonic plates on both sides, and solidifies into new crust. This ridge system, approximately 70,000km long, wraps around the globe like the seam of a baseball (Macdonald 2001). As oceanic crust spreads, it thins, allowing hot mantle rocks to rise. Mantle upwelling beneath mid-ocean ridges undergoes decompression melting, and these melts rise buoyantly to the surface to form a basaltic, rather than serpentinitic, oceanic crust (White and Klein 2014). This causes molten rock from deep in the Earth (~30-60 km) to ascend to fill the void between the plates which in turn creates new seafloor and a volcanically active ridge. Once plates diverge, the lithosphere stretches, the crust thins, and becomes smaller than anywhere else on Earth. Mantle melts can have variable compositions, but most commonly mafic and felsic rocks. Mafic basalts are heavier and are more enriched with calcium and sodium whereas felsic rocks are lighter and contain more aluminum and silicon. Oceanic crust is denser than continental crust which causes it to sink below continental crust (Whitmarsh et al., 2001).

Generally speaking, MORs are categorized into either fast spreading or slow spreading ridges. The transform faults along the EPR are considered fast-spreading ridges. Fast spreading rates are greater than 90 mm per year and have an axial high of several hundred meters while slow spreading rates are generally between 10-40 mm per year with deep rift valleys 1-3 km deep (Macdonald 2001). The EPR spreads at around 110 mm per year (Macdonald 2001). Fast spreading ridges have less uplift along the ridge as well as a gentler slope away from the ridge on both sides. Slow-spreading ridges, will have more uplift and steeper slopes away from ridges.

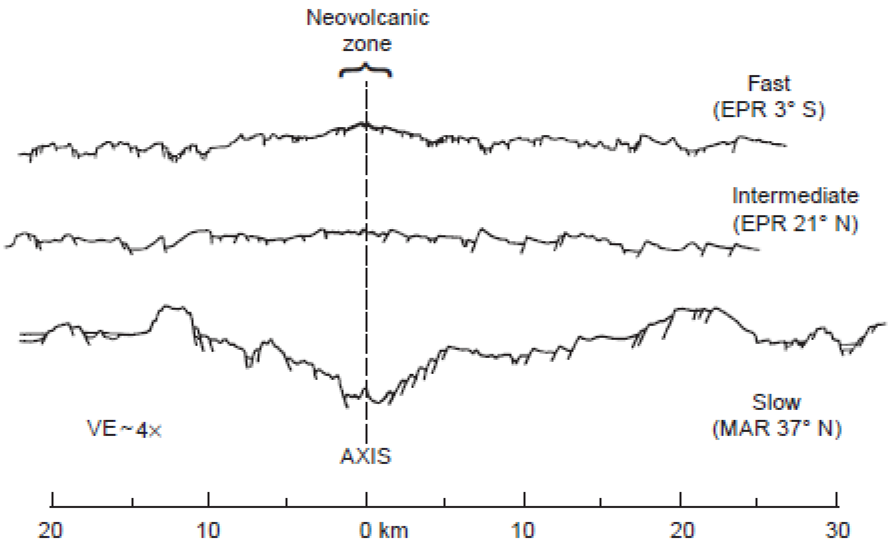

Figure 1- Cross sectional view of fast spreading EPR in the southern region, intermediate spreading in the northern region, and slow spreading in the Mid-Atlantic Ridge (Macdonald 2001).

Transform faults serve as connections between smaller segments of MORs; these MORs do not form consistently throughout the world, and are not equivalent line segments. Rather, they form multiple ridge segments that are bound by these transform faults. Because of this connection, it is important for us to study transform faults to determine whether they have the same properties and behaviors as the MOR segments that they connect. These faults form fracture zones that extend for thousands of miles away from the ridge, but they are only tectonically active in transform fault zones between ridges where plates are pulling in opposite directions. The actual location of these faults, and the origin of their seismicity is between the ridge segments where two plates grind against each other. Scientists have determined many processes occurring at transform faults, but cannot explain exactly why they are present. Transform faults are not the only offset occurring along mid-ocean ridges. Other offsets, commonly referred to as ridge axis discontinuities (RADs), come in many different forms, from larger transform faults to overlapping spreading centers and even small mobile breaks in the ridge (Macdonald, 2001).

These other discontinuities are still relatively mysterious to scientists. Ken Macdonald, professor at The University of California at Santa Barbara suggests that magma supply at these discontinuities is potentially less than magma along normal MOR segments. These studies found that erupted magma volume is a maximum in a cross-sectional area of the ridge near the centers of ridge segments, and that greater numbers of volcanoes occurred in the shallow mid-segment area than at the segment ends (Macdonald, 2001). Fast and slow spreading ridges each follow this pattern.

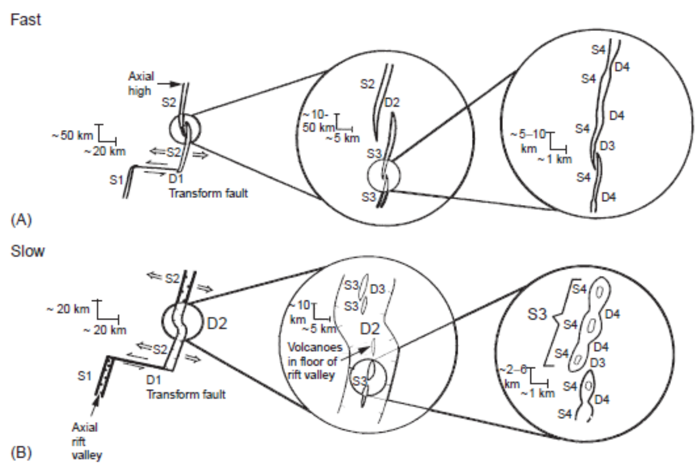

Figure 2- Types of RADs (ridge axis discontinuities) at (A) fast- and (B) slow-spreading ridges (Macdonald 2001).

This study also found that crustal magnetization was much greater near segment ends which shows locally limited magma supplies, but these magmas are iron rich. MgO concentration (in weight%), which correlates positively with eruption temperature and, perhaps, greater local magma budget, also shows a correlation with the axial-cross-sectional area, and hydrothermal venting (as measure by geochemical tracers and light backscatter) also varies directly with the cross-section (Macdonald, 2001). These interpretations are most relevant to fast-spreading ridges, but slow-spreading ridges do show similar results based on seismic and gravity data suggesting that oceanic crust thins the most near transform faults.

One explanation for this is that mantle upwelling is mostly concentrated near mid-segment regions, with less upwelling near their ends, which suggests a magma-starved region. However, another hypothesis claims that crustal thickness variations are the result of mechanical thinning caused by faulting. Both arguments are highly compelling, and really have no conflict between the two models. This makes it nearly impossible to say which idea is correct, or whether there is a combination of both occurring. Realistically each transform fault is going to behave differently from each other to some degree. Nevertheless, crustal thinning is mostly absent at the faster-spreading ridges. Macdonald suggests that fast-spreading ridges contain large, continuous chambers of magma that thin out slightly at discontinuities, and slow-spreading ridges have individual chambers between the discontinuities, with little magmatic activity. Consequently, we do not know exactly how these processes work at transform faults or how each transform relates to others. Therefore, this study aims to take a closer look at the Blanco, Clipperton, and Siqueros faults to try to gain some insight into this conundrum.

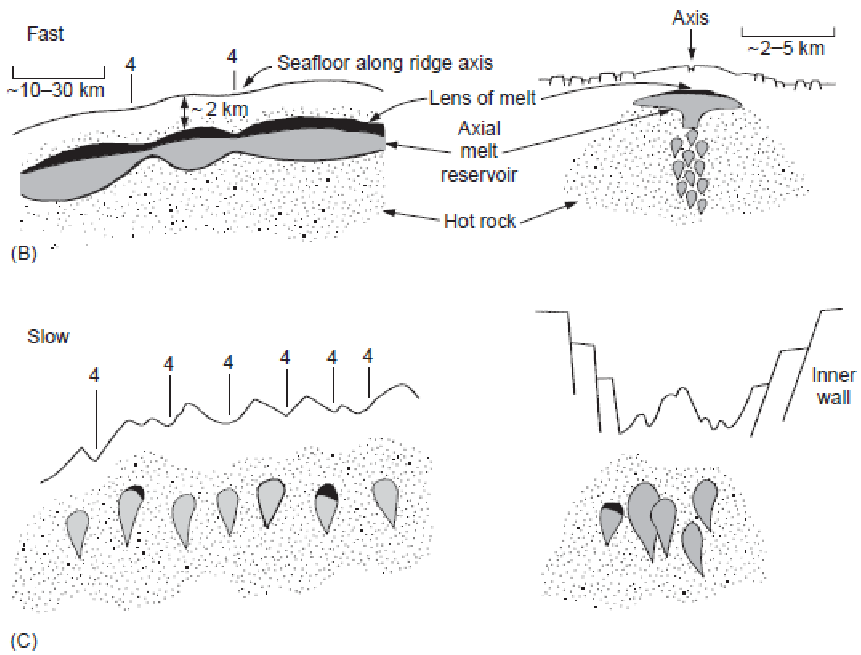

Figure 3: Parallel and perpendicular cross-sections of fast- and slow-spreading ridges showing discontinuities (numbered) and magma sources (Mcdonald 2001).

Previous studies of the Reykjanes, Juan da Fuca and the Northern Pacific Rise ridges showed that pressures of crystallization near transform faults can be very high (Scott & Barton 2010;

Zerda, 2014). The calculated pressures can reach 1000 M Pa and higher, which are much higher than the 200–300 M Pa average seen at normal ridge segments. These results tend to agree with the hypothesis of Claude Herzberg in his paper "Partial Crystallization of Mid-Ocean Ridge Basalts in the Crust and Mantle". Magmas along transforms partially crystallize in both the crust and upper mantle, and that the high pressures of partial crystallization reflect the fact that the deep crust and upper mantle are cooler along transforms than beneath normal ridge segments (Herzberg 2004). To explore this hypothesis, the study reported herein focuses on magmatism along transforms in the East Pacific Rise, specifically geochemical analysis and the calculation and interpretation of crystallization pressures. The current study investigates whether crystallization happens at a certain depth or over a wide range of depths. If crystallization occurs at a specific depth, oceanic crust composition should be uniform. If it occurs over a range of depths, the composition will be variable based on depth of crystallization. Some magmas may crystallize below the crust, in the mantle, and will show high pressures of crystallization. In Atlantic transform faults we see variability in crystallization pressures, so we focused on the East Pacific Rise for this research to see if they behaved in a similar manner.

Methods

For my research we extracted data from an online petrological database, www.petdb.org which is funded by the National Science Foundation. This database has data from samples collected at sites all around the world. We refined our search to include only glass samples and downloaded the data set. Glass samples are most useful to us because they cool so quickly that their composition preserves that of its magma, with no time for the lava to become contaminated with other elements that are found in sea water. The data downloaded that are relevant to this research include latitude, longitude, oxide compositions and weight percentages for samples collected at each location. Next we converted our iron oxides into total iron. Afterwards, we imported the data into a program called GeoMapApp where we could see all the data points on a world map and examine where they occurred on the 3 transform faults that were studied. Samples that were taken adjacent to the transform ridges and sea mounts were excluded as were as duplicate analyses and incomplete analyses.

Once the data sets were edited, we calculated the pressure of crystallization using the methods of Kelley and Barton (2008). The following relationship between pressure (P, in megapascals) and depth (z in in meters) was used to calculate the depth of partial crystallization:

$$P = \rho g z$$

with ρ as the density of oceanic crust (2900 kg/m^3) and g the acceleration due to gravity, 9.81 m/s^2. This calculation took into account the effect of the column of seawater using a density of 1000 kg m^{-3} for seawater as recommended by Dr. Barton. The correction for the column of seawater converts all depths to depths below the seafloor and is necessary for comparison with the results of seismic studies.

From here we transferred the data to a program that calculated the pressures at which each sample was formed. These pressures correlate to the depth of formation of the associated magma. We can then compare these pressures to MORs to see if they have similar pressures and therefore depths of formation, or if there are discrepancies. The major oxides were plotted against each other to show elemental trends during crystallization. We chose three transforms for this study, the Blanco, the Clipperton, and the Siqueros whose localities are displayed in figures 4–6.

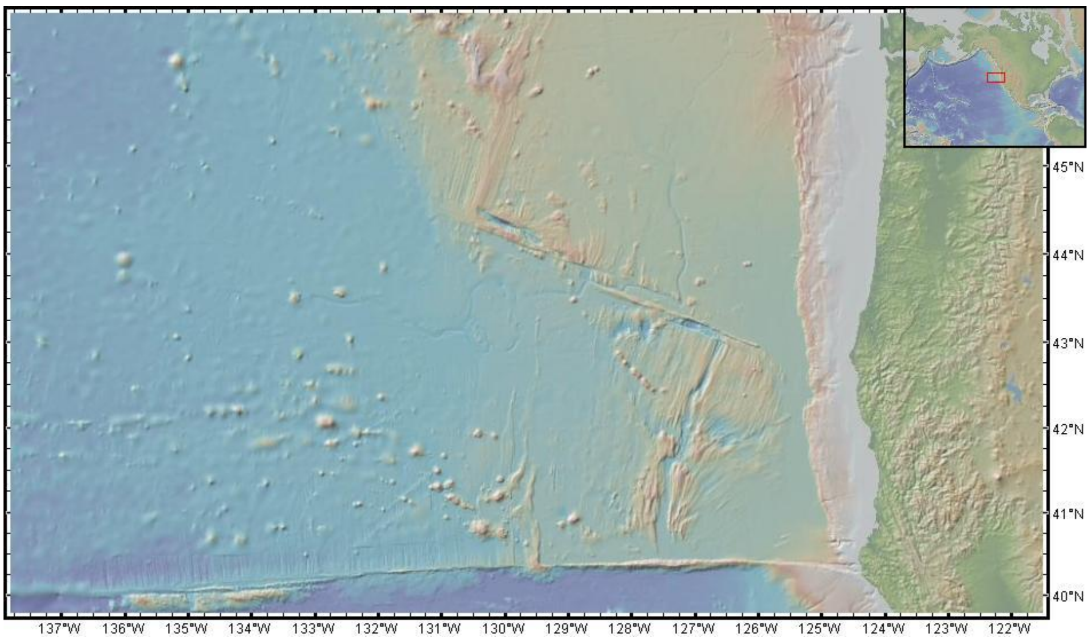

Figure 4– Geography of the Blanco transform fault, located between 43°N-44°N, 131°W-127°W. Made using GeoMapApp.

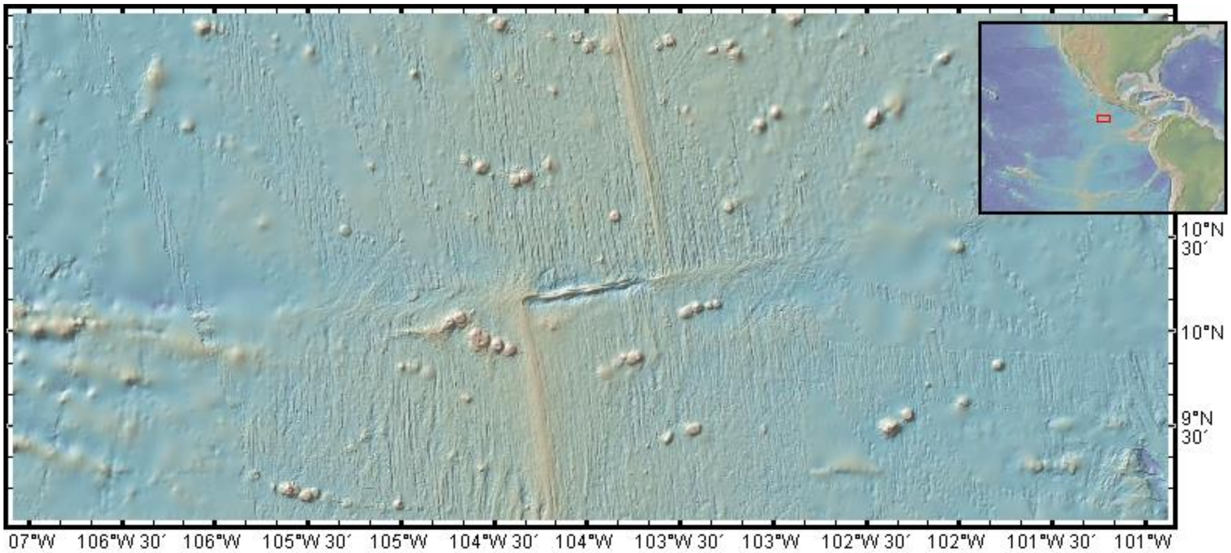

Figure 5 – Geography of the Clipperton transform fault, located between 10°N-10°N 30’, 104°W 30’-103°W 30’. Made using GeoMapApp.

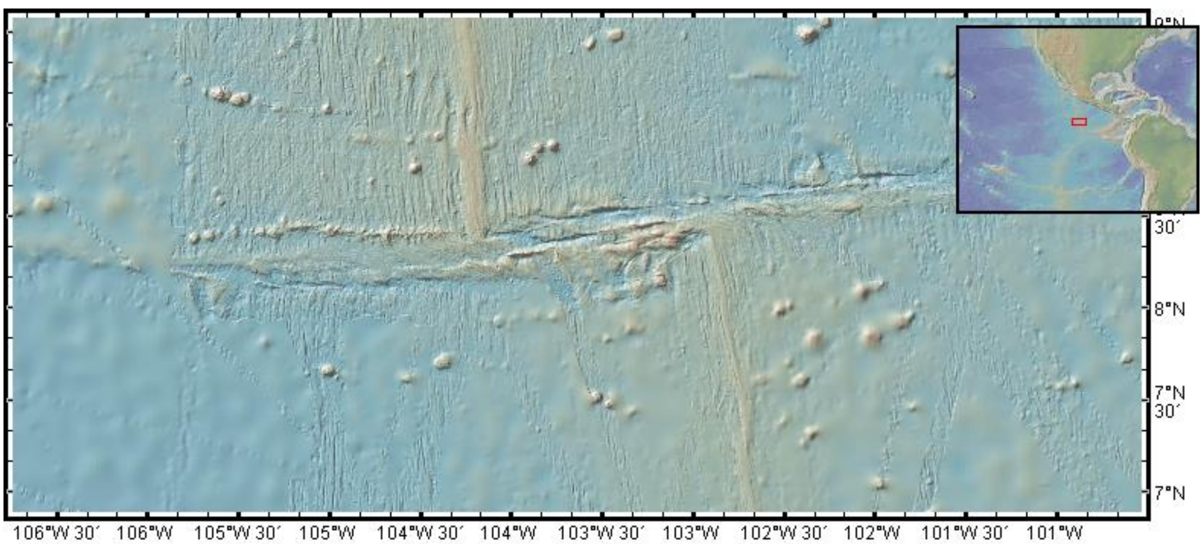

Figure 6 – Geography of the Siqueros transform fault, located between 8°N 15’-8°N 30’, 104°W 30’-103°W. Made using GeoMapApp.

Results

The methods used to calculate the pressures of partial crystallization are calibrated for liquids in equilibrium with the mineral assemblage olivine-plagioclase-clinopyroxene (opc). Therefore, it is necessary to identify melt compositions that crystallized the opc assemblage. We plot against MgO because olivine is abundant in all basalts, so we can compare the crystallization of other minerals to the crystallization of olivine. Such compositions will show a linear, positive relationship between MgO and CaO on variation diagrams. MgO percentages will decrease as olivine crystallizes out of the melt, CaO will decrease as clinopyroxene crystallizes, and Al_2O_3 will decrease as plagioclase crystallizes. Plots show weight percentages of oxides found in our glass samples. Composition of liquids that form clinopyroxene and plagioclase vary for different pressures. The plots in Figures 7, 9, and 11 show that MgO and CaO are positively correlated for the Blanco, Clipperton, and Siqueros respectively.

Plots of pressure are shown in kilobars which are equivalent to 100 M Pa. They are plotted versus latitude, longitude, and MgO (Figures 8, 10, 12) and indicate that pressures of crystallization vary along each transform in all directions. The majority of calculated pressures for each fault are between 0 and 500 M Pa with some reaching up to 1500 M Pa. The average crystallization pressure for MORB is 200-300 M Pa. Plots of pressure versus MgO (Figure 6) indicate that pressure decreased as olivine crystallized. We can also see that pressures are highest towards the center of each transform fault.

Blanco

The Blanco had fewer data compared to the other 2 transforms examined. Figure 7 shows results for the Blanco which display a negative correlation between MgO and TiO_2; MgO and total iron content (FeOT) also have a negative correlation. As MgO decreases, TiO_2 and FeOT increase.

SiO_2 is consistently 48-52% and does seem to increase with decreasing MgO. Al_2O_3 raises slightly between 7-8% MgO then steadily decreases afterwards. CaO has a slight positive correlation with MgO. Pressures are positively correlated with MgO and are generally consistent from 100-500 Megapascals with a few points anomalously high.

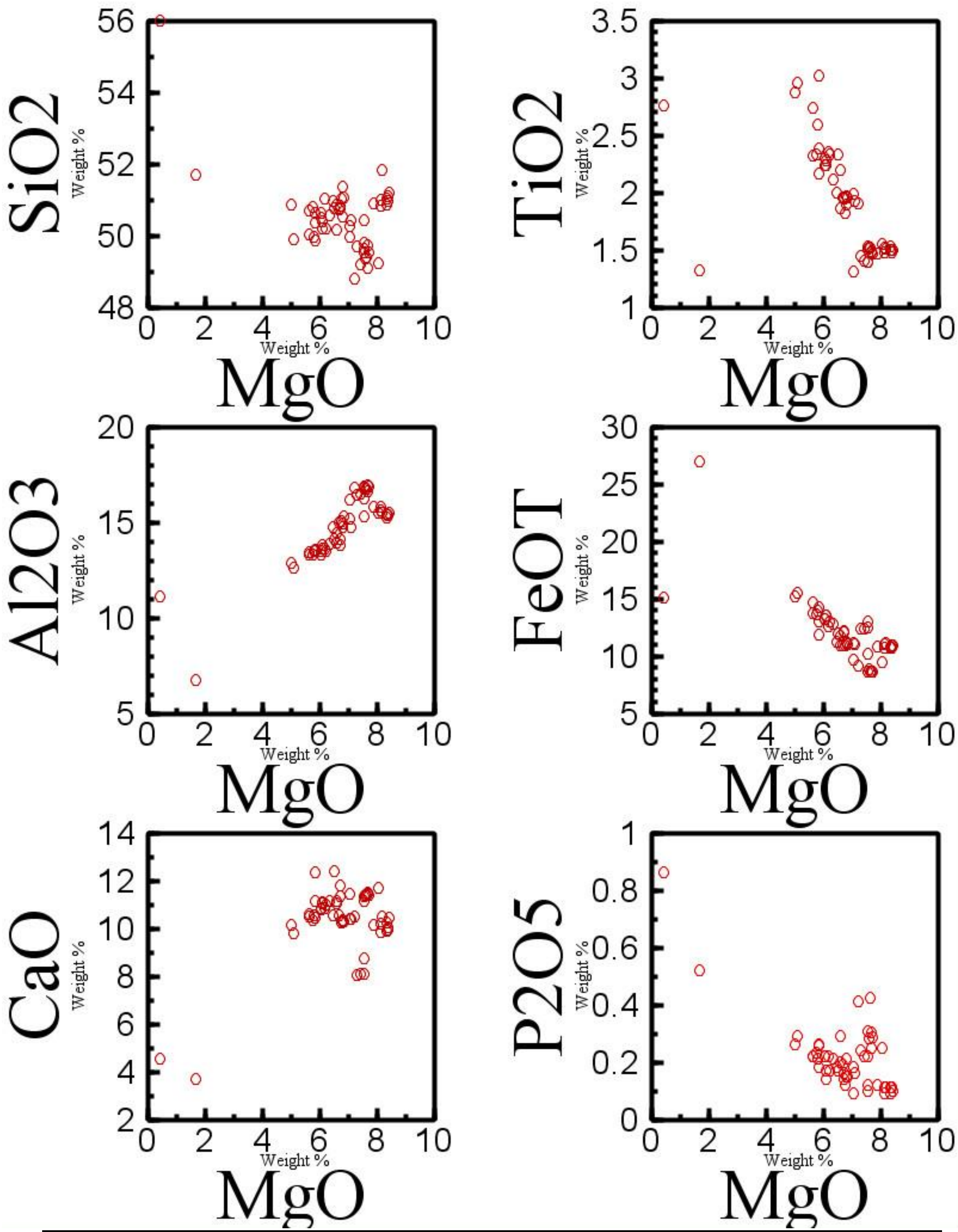

Figure 7- Plot of weight percentages of oxides versus weight percentages of MgO for the Blanco fault.

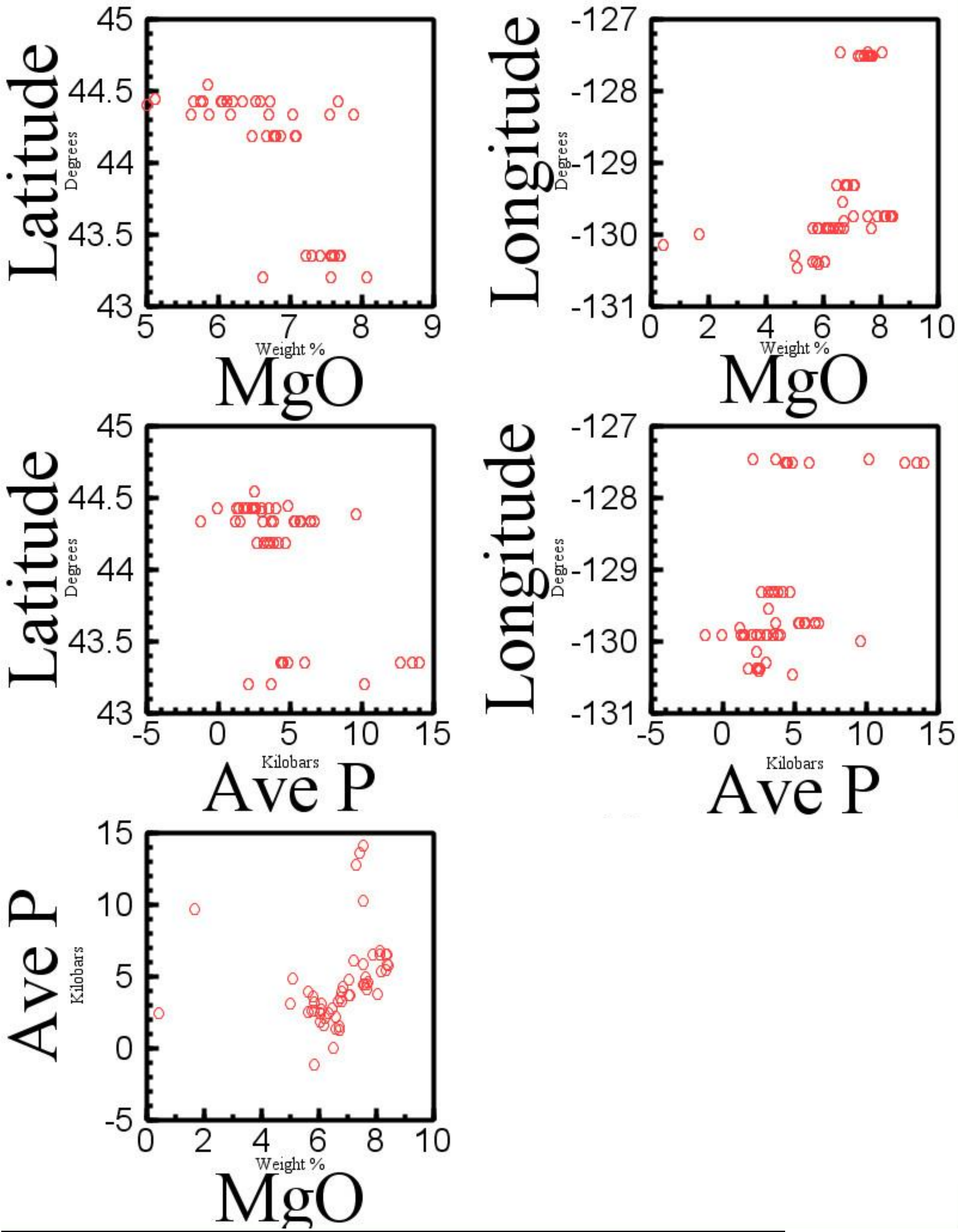

Figure 8- Plot of weight percentage of MgO versus latitude and longitude, plot of pressure versus latitude, longitude and percent MgO.

Clipperton

As shown in figures 9 and 10, the Clipperton had the most data available and also showed the best evidence for the anticipated geochemical trends. SiO_2 increases with decreasing MgO, TiO_2 does as well. Al_2O_3 increases with increasing MgO and Fe increases with decreasing MgO. CaO decreases with decreasing MgO and P_2O_5 increases with decreasing MgO. Pressure is consistently between 0–500 megapascals across the fault and even remains consistent with increasing MgO.

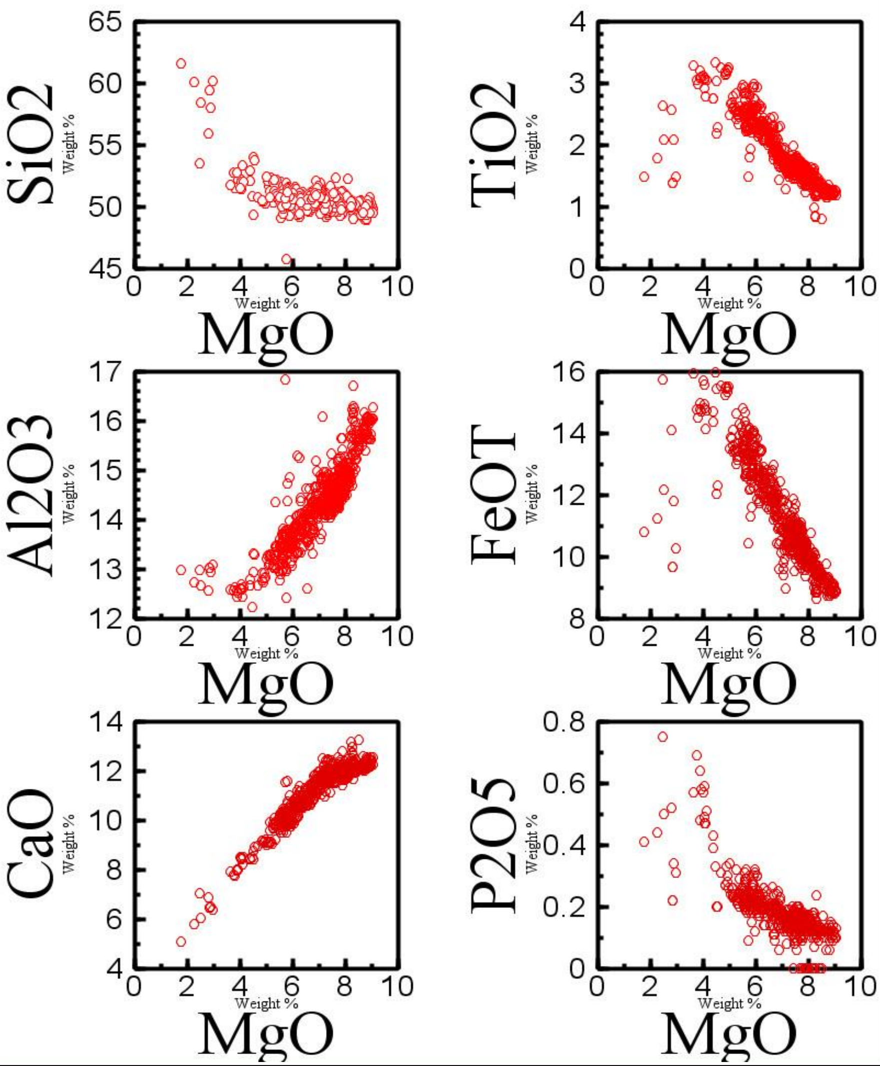

Figure 9- Plot of weight percentages of oxides versus weight percentages of MgO for the Clipperton fault.

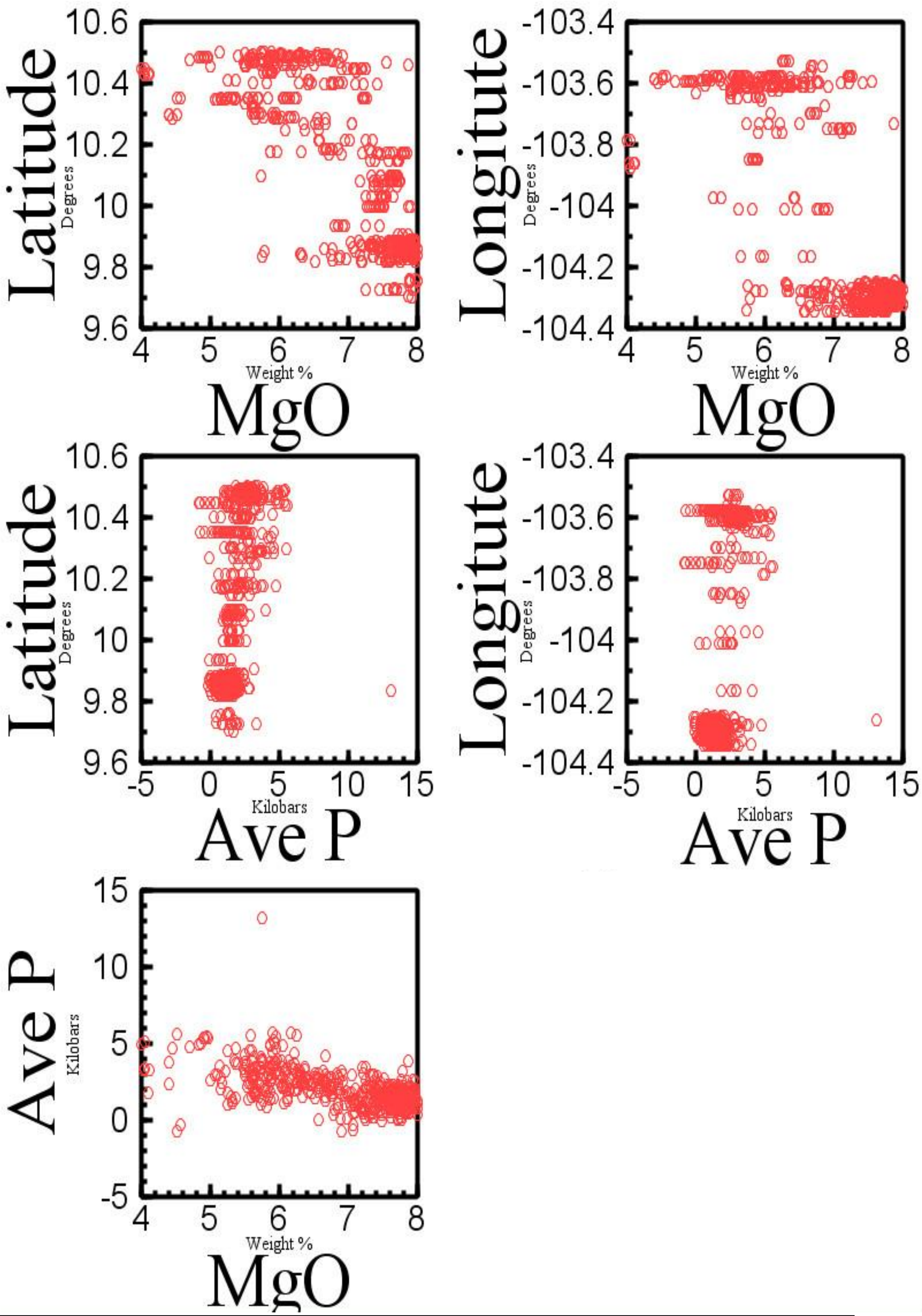

Figure 10- Plot of weight percent of MgO versus latitude and longitude; average pressure versus latitude, longitude, and weight percent of MgO for the Clipperton.

Siqueros

Figures 11 and 12 show that SiO_2 ranges from 46%-63% with most samples falling between 48-52%. Samples at 55% and above SiO_2, are too silica rich to be considered basalts. TiO_2 slightly increases until 10% MgO where it increases drastically. Al_2O_3 increases until 10% MgO where it falls sharply. Fe is generally consistent except between 5–10% MgO where it increases slightly. CaO is positively correlated with MgO until around 10% MgO where the CaO starts to decrease. P_2O_5 decreases sharply until 10% MgO where it evens out under 0.1%. MgO content and pressures range very high to very low at this fault and is consistently lower away from the fault. Pressure increases with increasing MgO and is consistently between 0-1000 megapascals at different locations besides a few outliers that reach pressures over 1500 megapascals.

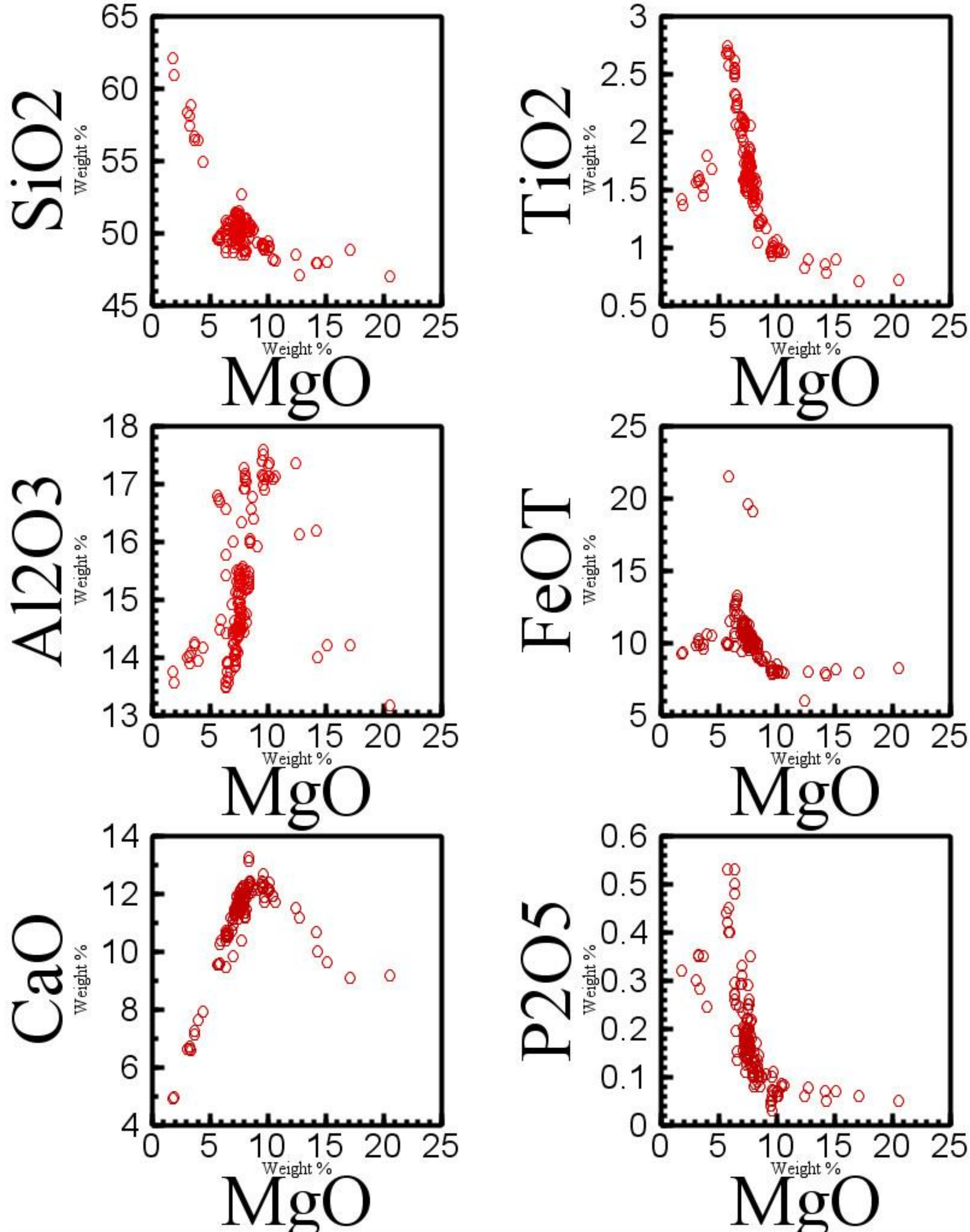

Figure 11- Plot of weight percentages of oxides versus weight percentages of MgO for the Siqueros fault.

Discussion

Some of the pressures calculated for this research are unreliable and not pertinent to this study because they are either negative or are associated with large errors (126 MPa – the error deemed acceptable by comparison with experimental data). All pressures more negative than -126 MPa are filtered out of the data, whereas pressures between -126 and 0 MPa are changed to 0. Global studies of MORB show that samples with MgO contents greater than 8 weight % do not lie along the liquid-olivine-plagioclase-clinopyroxene cotectic, so samples above 8% MgO should be disregarded. Graphs for the filtered results (P versus longitude and P versus MgO) indicate that pressures are usually at or below 1000 M Pa for three transforms, but are closer to 500 mPa on average. This is higher than pressures calculated for normal ridge segments (Scott et al., 2010, 2012, 2013). Samples for these three transforms show a linear, positive relationship between MgO and CaO on variation diagrams consistent with magma evolution via crystallization of olivine, plagioclase and clinopyroxene. The results for these transforms are therefore considered to be robust and reliable.

Melt compositions and pressures vary in all three faults, which shows that crystallization happens at different depths. In figures 8, 10, and 12 pressures get lower as we move away from the transform laterally. Herzberg (2004) showed that pressures of partial crystallization of olivine+plagioclase+clinopyroxene range from 1 atm to 1.0 GPa. The pressures calculated from glasses at the transforms in this study are in agreement with this pressure range. The average pressures for these magmas are higher than the 200–300 mPa we see for normal MOR segments (Herzberg 2004). There are likely regional variations that generally correlate with spreading rate that would affect the composition and pressures for each fault.

The Clipperton has the most consistent data of the transform faults and shows distinct pressure and crystallization trends. The plots of geochemical trends look smoother for the Clipperton compared to the Blanco or Siqueros. The Siqueros is next highest in terms of pressures, and the Blanco is generally between 100 and 500 M Pa. All 3 faults have positive correlations between MgO and CaO. They also show positive correlations between MgO and Al_2O_3 as well as between MgO and pressure of crystallization.

According to Perfit et al., “Siqueros picritic basalts formed by the accumulation of olivine and minor spinel in relatively high MgO basaltic melts (10–14% weight) rather than equilibrium crystallization of more mafic liquids with 14–20% MgO. Their calculated liquidus temperatures for high MgO (around 11.6%) liquids range from 1340-1240 degrees C with pressures of 1000 mPa or less” (page 102). We do see results that support Perfit’s work in the samples that we studied. Although it is difficult to correlate certain crystallization pressures to specific processes occurring beneath these transform zones, “polybaric, incremental batch accumulative melting is likely to represent closely the process whereby melts have formed below the Siqueros transform domain” (Perfit et al., page 102). Perfit has done abundant research on this particular fault and even believes that “ductile shear zones are likely to exist beneath the [Siqueros], and could facilitate melt extraction and explain relatively large extents of melting” (Perfit et al., page 104). The Clipperton and Blanco faults had more consistent results than the Siqueros, so the same conclusions cannot be drawn for them. Perfit et al. also explains that “in contrast, the normal range of MORB compositions from intra-transform spreading centers requires small, but frequently replenished, crustal melt lenses and lithospheric magma plumbing systems beneath the intra-transform spreading centers” (Perfit et al., page 104). This is likely a better fit to explain the pressures we see from the Blanco and Clipperton.

Based on the results obtained in this work, pressures along transforms are not anomalously high compared with those along normal mid-ocean ridges, but do show some higher calculated crystallization pressures. Transform faults are not so inconsistent as previously believed. Few of the pressures calculated in this work are extremely high, and the high pressures are calculated for samples with unusual chemical characteristics, which could be an indication that these samples were transported from another source or even errors while transferring data. In essence, the results for these samples are not deemed reliable. Most of the data are very reliable though and shows very nice elemental trends as well as pressures consistent with data published for other transform faults.

Future work

Continuing this research in the future, one should analyze hand samples, thin sections, and perform spectrometry analysis to determine the composition and overall make up of glasses in these regions. I relied upon data published in an online database, and being able to analyze physical samples would greatly enhance this research. Analyzing more samples will validate or refute the overall trends of compositions and pressures. Comparing these results with other ridge segments, especially other fast spreading ridges as well as slower spreading ridges like that of the mid Atlantic would be beneficial in understanding the global processes of all MORs. Because these faults do follow expected geochemical correlations between oxides, I think that future research linking attributes of these faults with others in the Pacific would be extremely valuable to the geologic community.

Conclusions

Although this study does not prove how transform fault processes behave and interact, it does show that each fault expresses crystallization behavior that we did expect to see. Despite the three faults showing similar correlations with expected geochemical trends, they each vary in their own way. This is not necessarily a bad thing, as it shows that there is a lot of variation within these particular segments. The Blanco, Clipperton, and Siqueros transform faults show behavior similar to MORs but also show pressures higher than 200–300 mPa. The Clipperton had the most data and its results resembled trends from MORs more so than the other 2 faults that were studied. According to White and Klein 2014, "compositional heterogeneity is inversely correlated with spreading rate: more homogeneous lavas erupted on faster spreading ridges, probably reflecting the greater thermal stability and longevity of sub ridge crustal magma bodies, as well as, perhaps, higher eruption frequencies" (Page 463). The faults from the EPR in my research are fast spreading and do show homogeneity. I believe that these transform faults do share a parent magma but likely have their own specific plumbing systems that transport their magmas to the spreading areas.

References

Herzberg, C. (2004) Partial Crystallization of Mid-Ocean Ridge Basalts in the Crust and Mantle, *Journal of Petrology*, *45*(12), 2389–405, doi:10.1093/petrology/egh040.

Kelley, D. F., and M. Barton (2008) Pressures of Crystallization of Icelandic Magmas, *Journal of Petrology*, *49*(3), 465–92, doi:10.1093/petrology/egm089

Macdonald, K. C. (2001) Seafloor Spreading: Mid-Ocean Ridge Tectonics, *Encyclopedia of Ocean Sciences*, Academic Press, pp. 1798–1813.

Perfit, M.R., D.J. Fornari, W.I. Ridley, P.D. Kirk, J. Casey, K.A. Kastens, J.R. Reynolds, M. Edwards, D. Desonie, R. Shuster, & S. Paradis. (1996) Recent Volcanism in the Siqueros Transform Fault: Picritic Basalts and Implications for MORB Magma Genesis. *Earth and Planetary Science Letters,* 141:91–108,

Scott, J. L. & Barton, M. (2010) Pressures of Partial Crystallization of Magmas from the Juan de Fuca Ridge: Implications for Crustal Accretion. *2010 Fall Meeting, AGU*. San Francisco, Calif.

Scott, J. L., Kelley, D. F. & Barton, M. (2012). Petrological Constraints on Magma Plumbing Systems along the Reykjanes and Juan de Fuca Ridges. *2012 Fall Meeting, AGU*. San Francisco, Calif.

Scott, J. L., Kelley, D. F. & Barton, M. (2013). Refined Petrological Constraints on Magma Plumbing Systems along the Reykjanes Ridge. *2013 Fall Meeting, AGU*. San Francisco, Calif.

Zerda, C. (2014) Partial Crystallization in the Deep Crust at the East Pacific Ridge: A Study from 8°N to 14°N, B.S. thesis, The Ohio State University, Columbus, Ohio, 36 pp.

Whitmarsh R., Manatschal G., & Minshull T. (2001) Evolution of magma-poor continental margins from rifting to seafloor spreading, *Nature*, Vol. 413 (6852):150–154.

White, W.M. & Klein, E.M. (2014) Composition of the Oceanic Crust Treatise on Geochemistry (Second Edition), (2014), Second Edition, pp. 457–496.